Investigation of the Combustion Chamber Acoustics and its Interaction with LOX/H_2-Spray Flames

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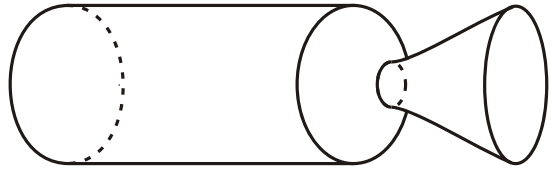
in der Helmholtz-Gemeinschaft

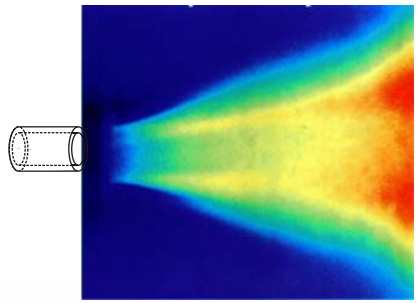
HF combustion instabilities

coupling of acoustic combustor resonances to combustion processes

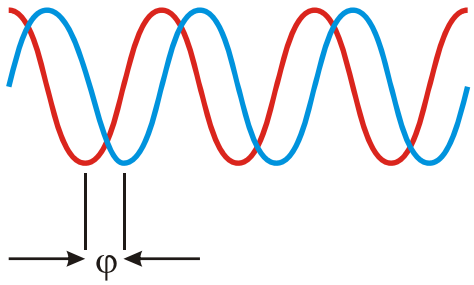
- chamber acoustics
  - eigenmodes of a cylindrical resonator



- combustion processes
  - propellant injection
  - atomization
  - secondary atomization
  - droplet evaporation
  - chemical kinetics



coupling mechanisms



pressure fluctuations p'

Rayleigh criterium

$$\iiint \int_0^{2\pi} p'\dot{q}'\, dt\, dV > 0$$

heat release fluctuations $\dot{q}'$

coupling due to

acoustic pressure

acoustic velocity

???

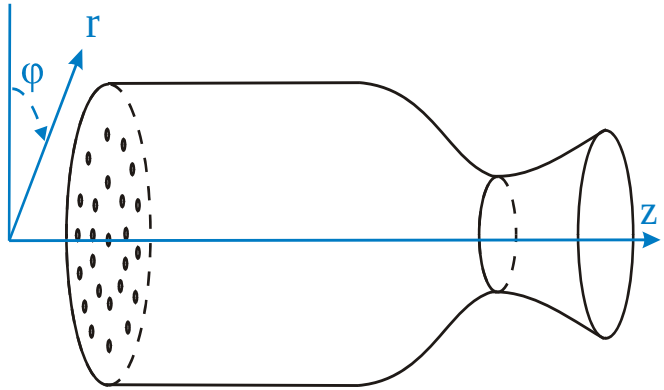
- injection
- evaporation
- chemical kinetics

- atomization
- evaporation
- mixing

combustion chamber as acoustic resonator

- chamber in good approximation treated as cylindrical volume
- chamber acoustically closed at the throat
- linear acoustics

$$\frac{\partial^2 P'}{\partial t^2} - c^2 \Delta P' = 0$$



- Eigen value equation

$$\Delta P' = -\frac{\omega^2}{c^2} P'$$

$$P'(z,r,\varphi) = \cos(n\varphi) J_n(\alpha_{nm} \frac{r}{R}) \cos(l\pi \frac{z}{L})$$

l = 0, 1, 2 … longitudinal modes

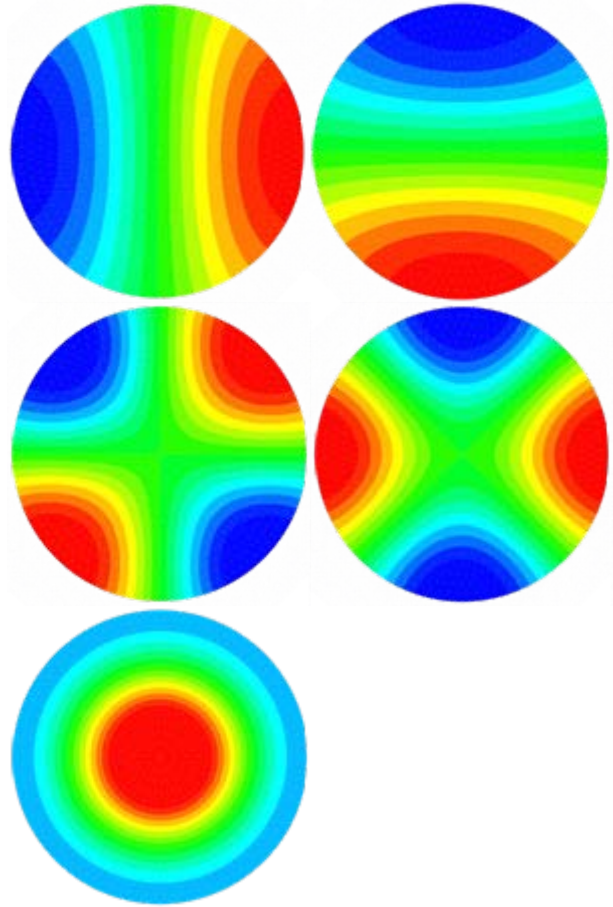
n = 0, 1, 2 … tangential modes

m = 1, 2, 3 … radial moden

eigen modes of a cylindrical resonator

$$f_{nm} = \frac{\alpha_{nm} c}{2\pi R}$$

Mode	n	m	α_{nm}
1T	1	1	1.841
2T	2	1	3.054
1R	0	2	3.832
1T1R	1	2	5.331



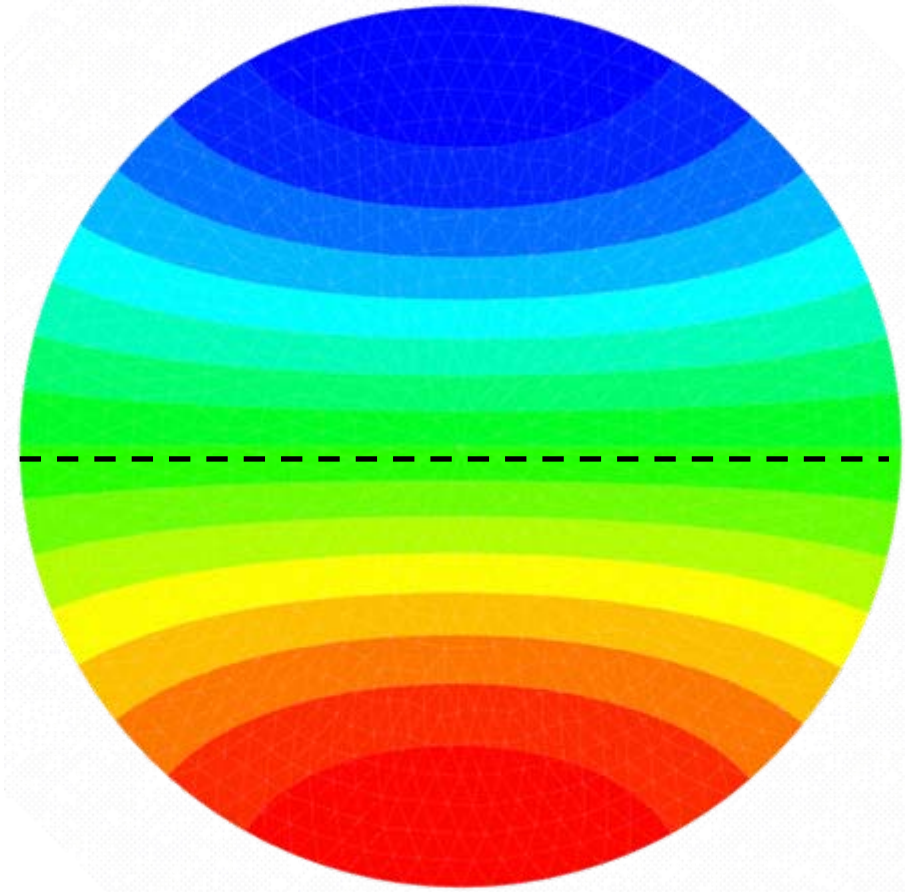
$$R \approx 0.1m$$

- ambient air:
  $c = 343 m/s$
  $f_{1T} = 1.0 kHz$
- hot fire test:
  $c \approx 1370 m/s$
  $f_{1T} = 4.0 kHz$

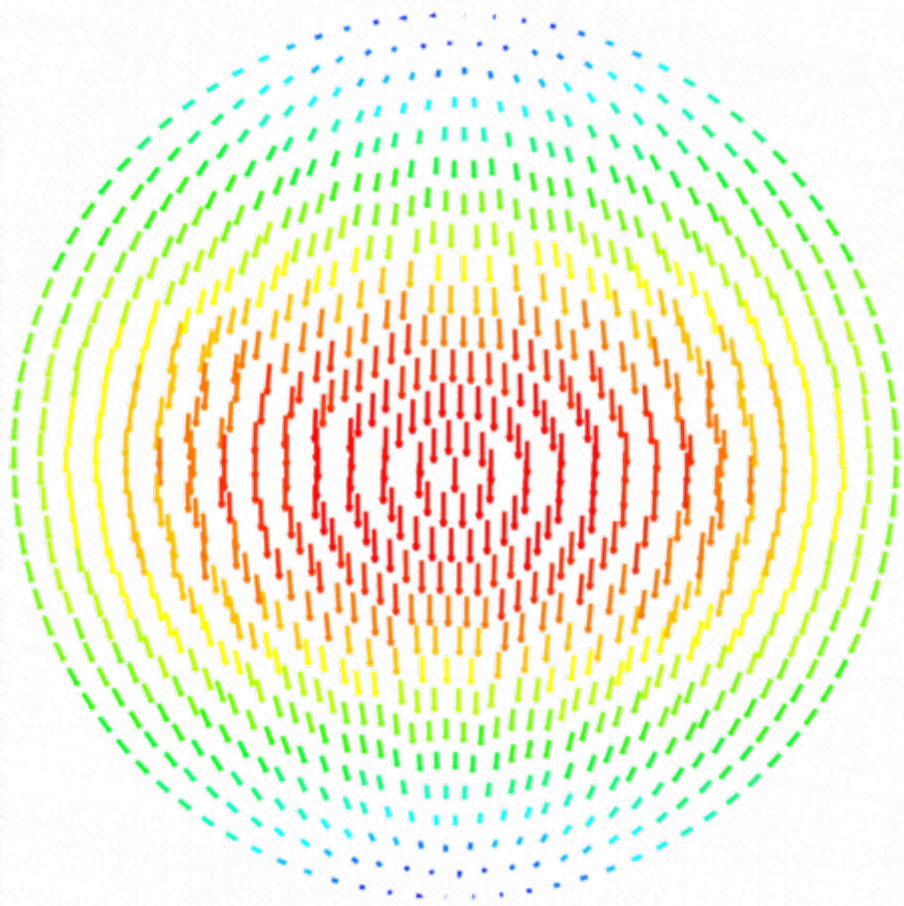
- tangential modes are 2-fold degenerate
- usually longitudinal modes not involved in HF-instabilities

1T eigen mode

pressure field

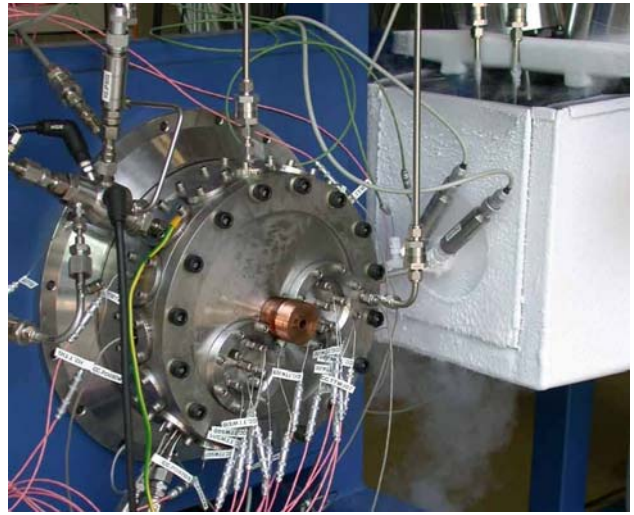


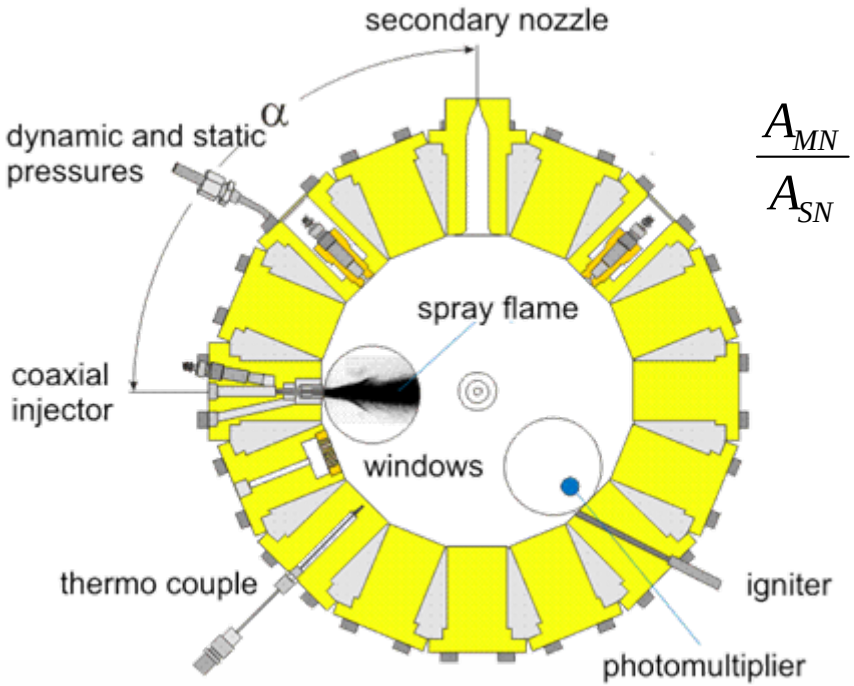
velocity field



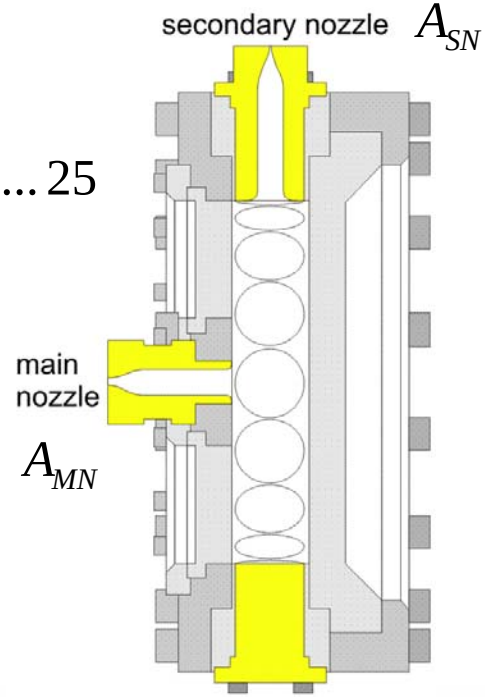
HF-combustor (CRC)

- diameter x height: 20 cm x 4 cm
- transversal modes at representative frequencies
- p_C up to 10 bar
- LOX, GH_2 @ 77K
- coaxial injector
- injection in radial direction

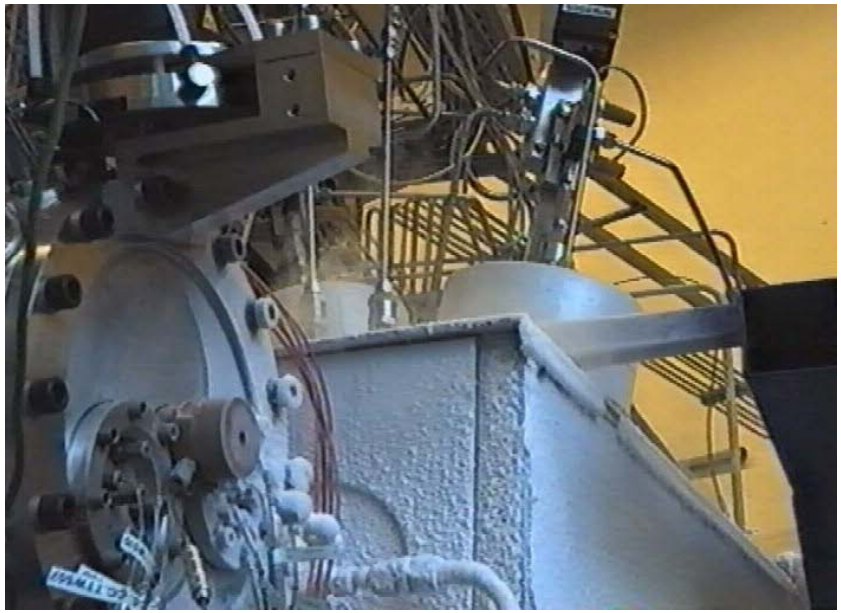


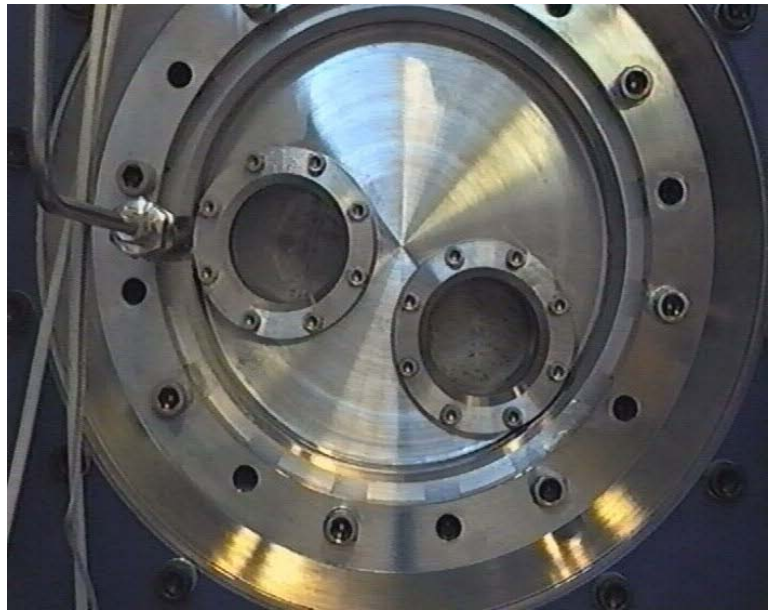


$$\frac{A_{MN}}{A_{SN}} = 6 \ldots 25$$



LOX/H_2-spray combustion in the CRC



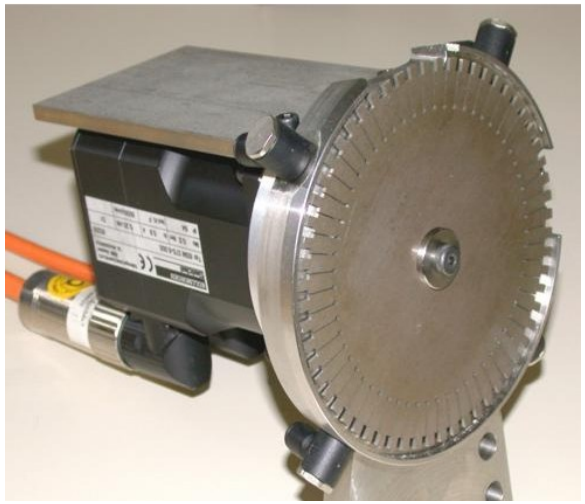


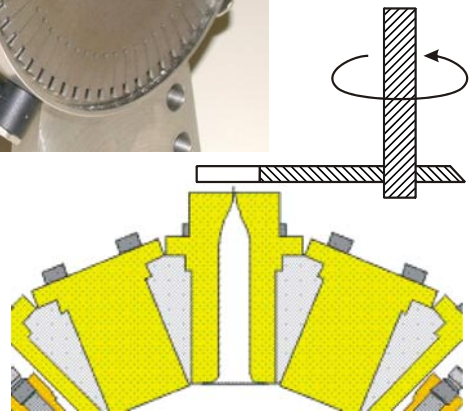
external excitation by siren

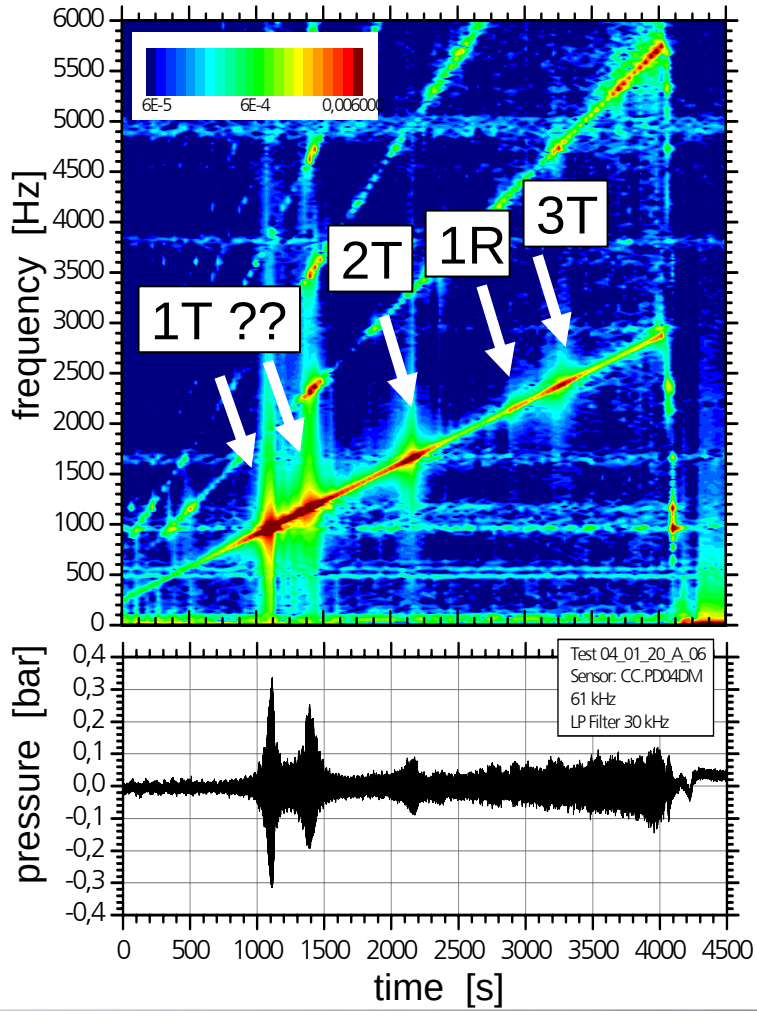
ambient air

mode	(349 m/s)
1T	1022 Hz
2T	1695 Hz
1R	2127 Hz
3T	2332 Hz

- siren at secondary nozzle exit
- frequency ramping during test with 500 Hz/s

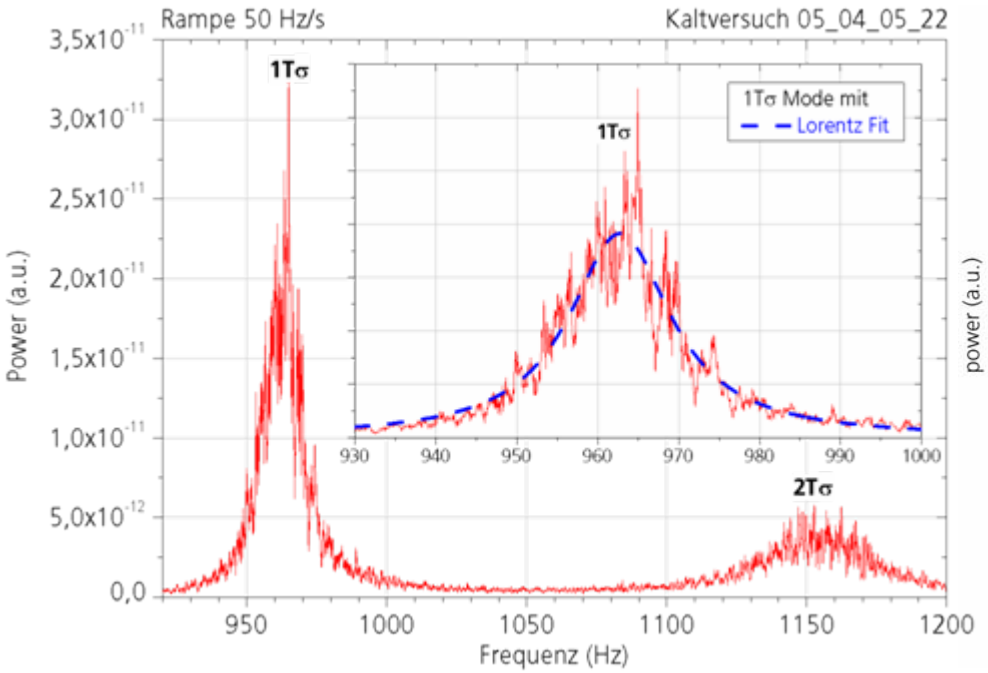


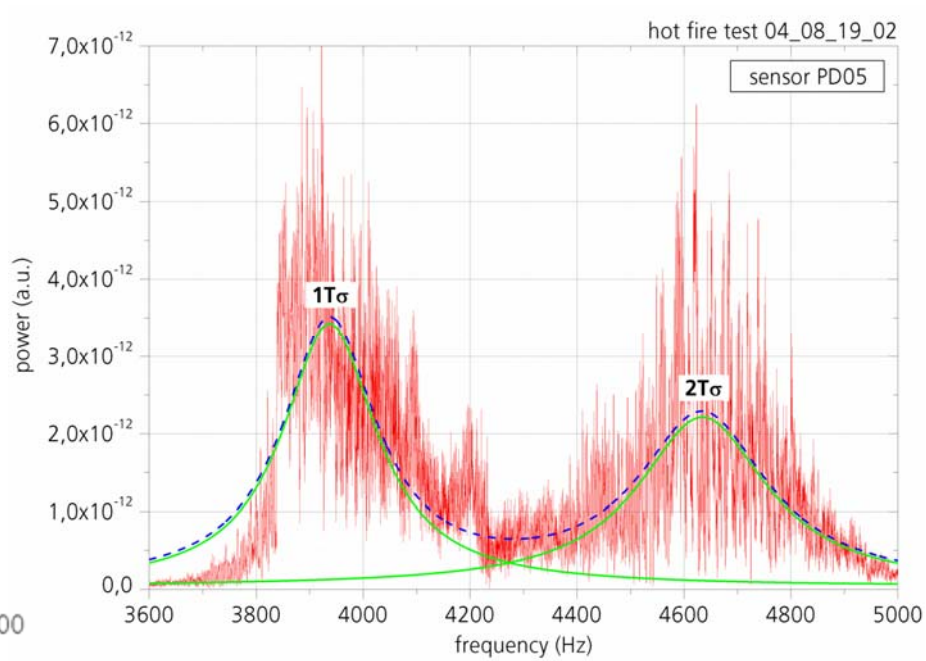




resonances near 1T-cylinder mode in combustor with secondary nozzle

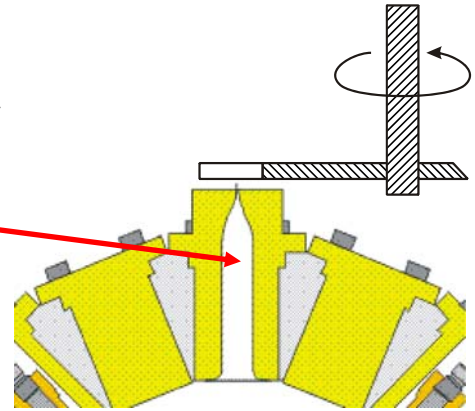
- "noisy" appearance of resonances with siren excitation
- hit fire tests: line width and asymmetric profile indication for combustion/acoustics interaction

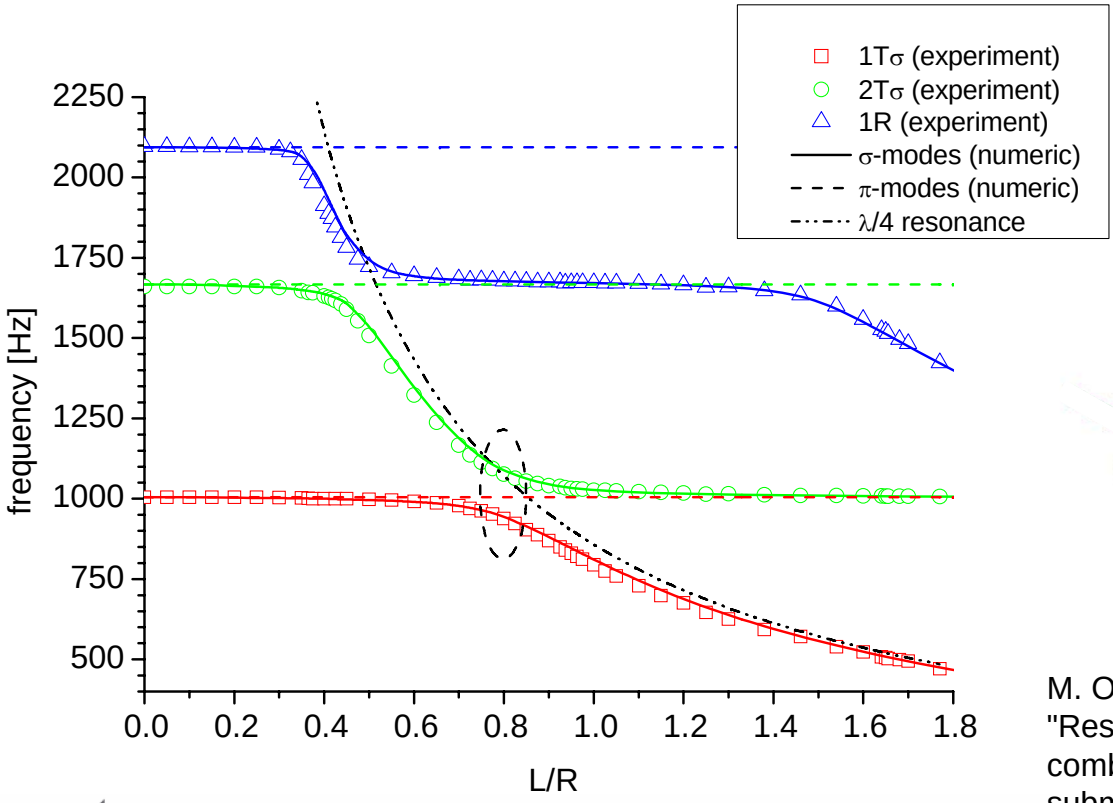


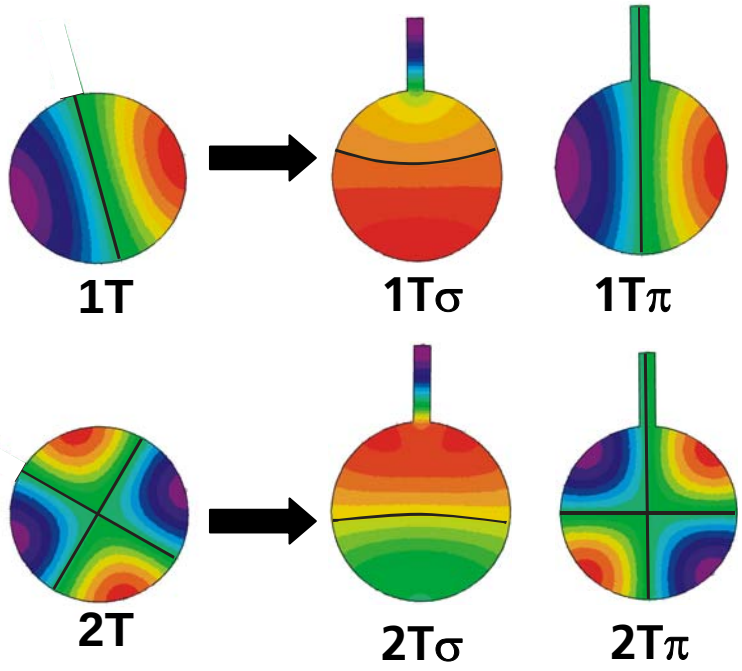


eigenfrequencies of cylinder with cavity

- secondary nozzle forms additional resonance volume
- cavity breaks 2-fold degeneracy of tangential eigenmodes
  - two eigenmodes of different symmetries and eigenfrequencies
- N.B.: analogy to λ/4-absorbers



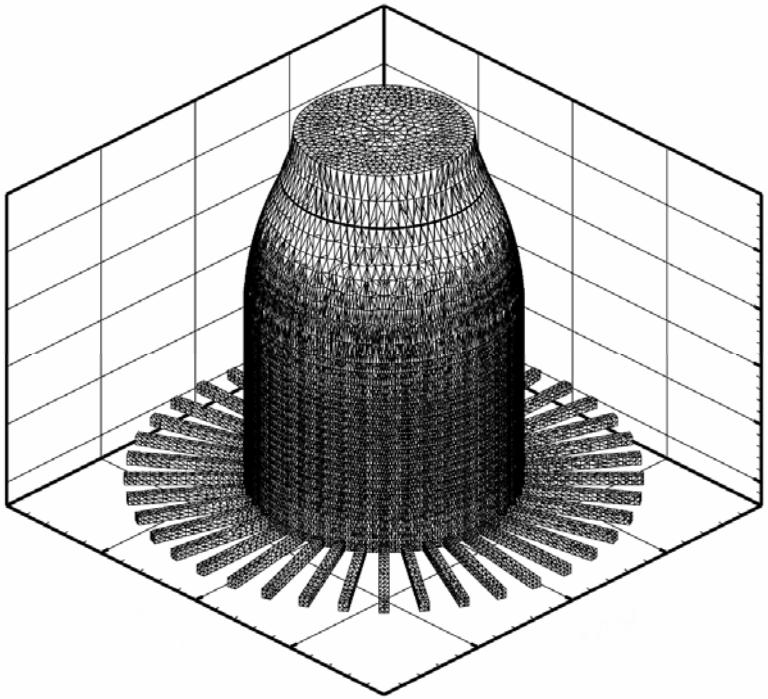


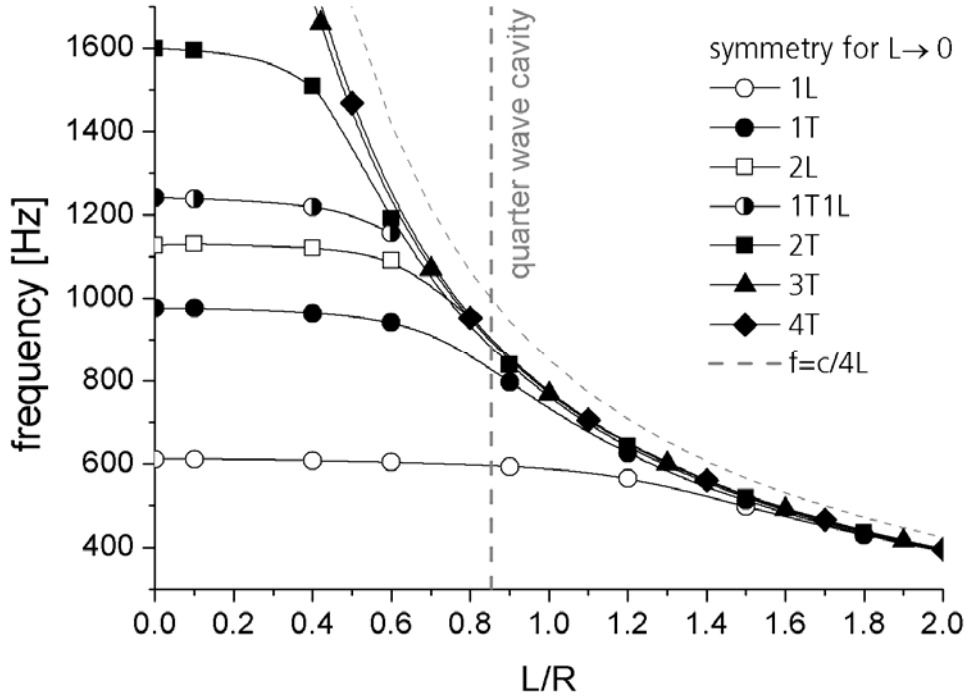


M. Oschwald, Z. Farago, G. Searby, F. Cheuret, "Resonance frequencies and damping of a cylindrical combustor acoustically coupled to an absorber", submitted to Journal of Proulsion and Power, June 2007

eigenfrequencies for combustor with absorber ring

- first 8 low lying modes analyzed
- absorber ring detunes acoustic system
- modes group near to the cavities λ/4-resonance

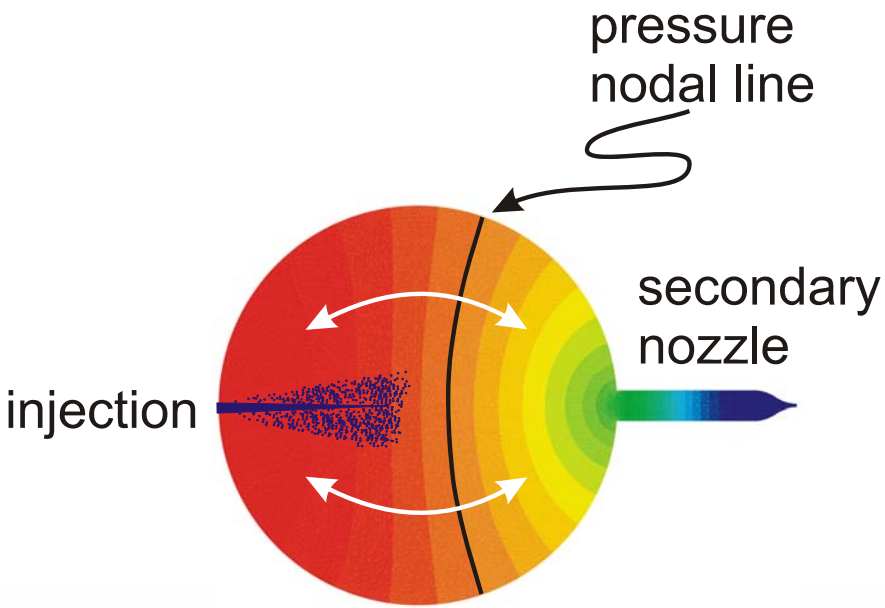


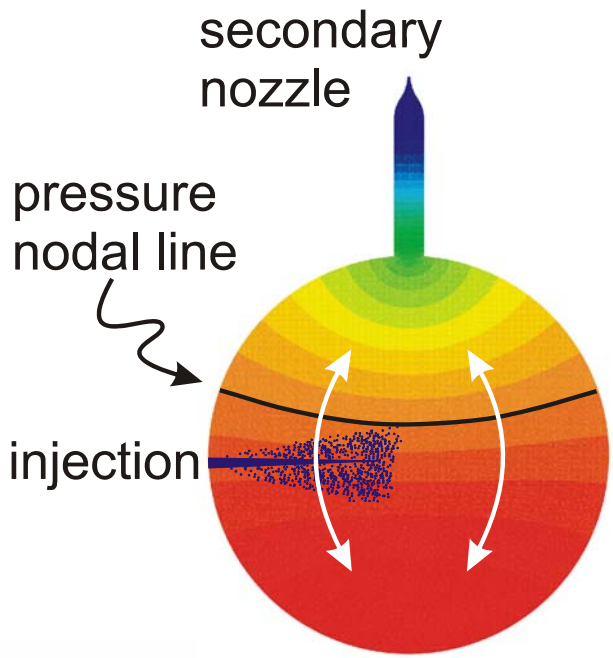


pressure distribution for SN at 90° and 180°

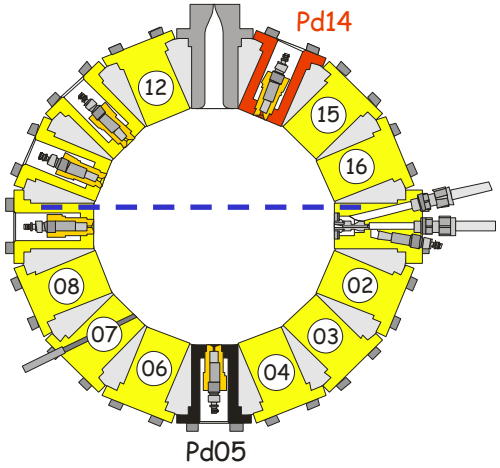
SN at 90°
- spray exposed to strong acoustic pressure fluctuation
- no transversal velocity fluctuation

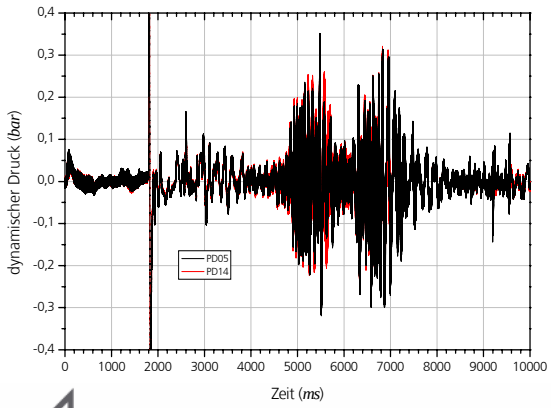
SN at 180°
- spray exposed to strong transversal acoustic velocity fluctuations
- very small pressure fluctuations

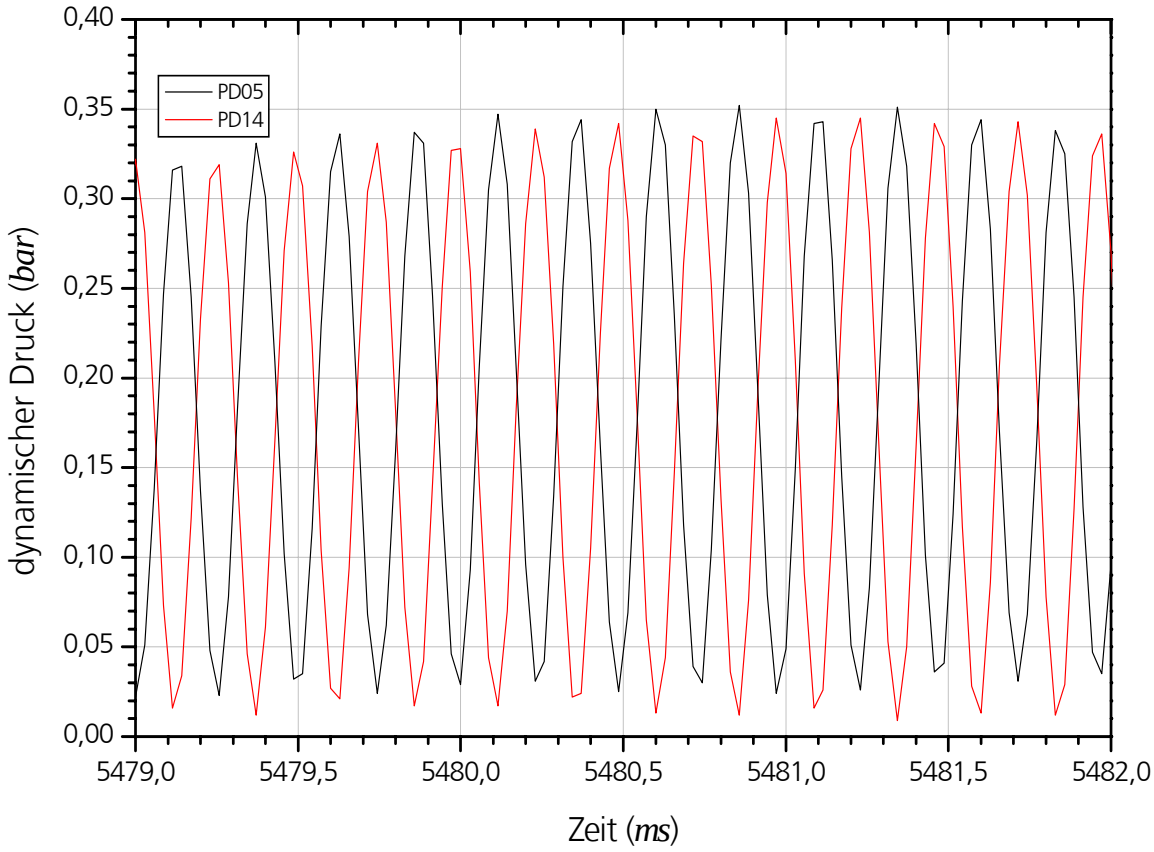




dynamic pressure on resonance for SN at 90°

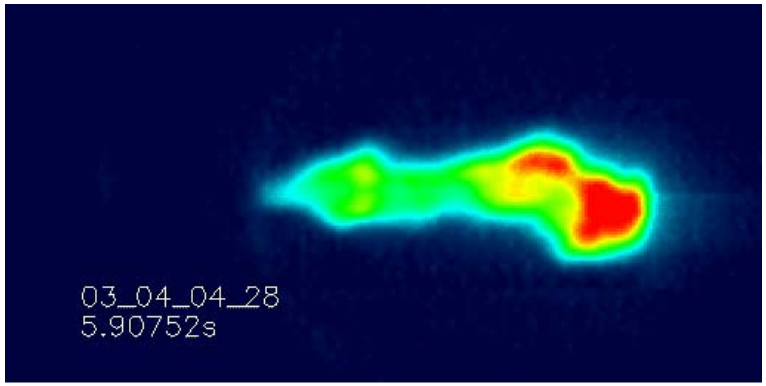


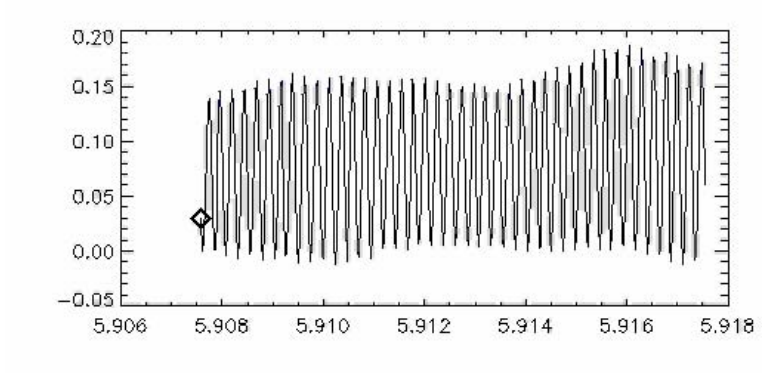




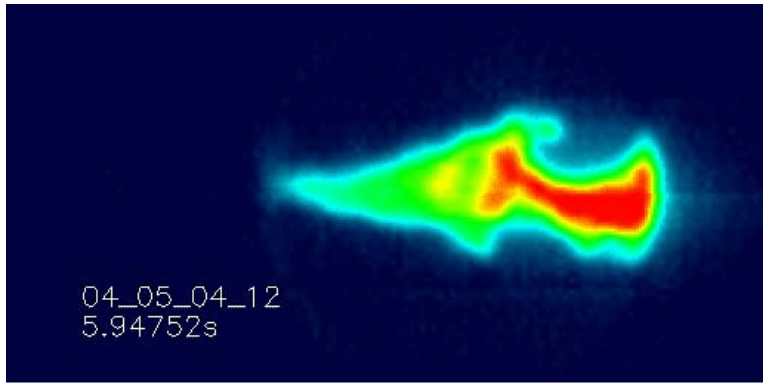
OH-chemiluminescence during excitation

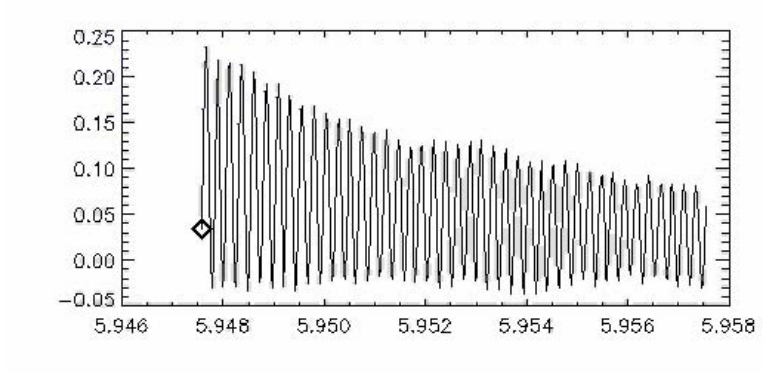
excitation with SN at 90°



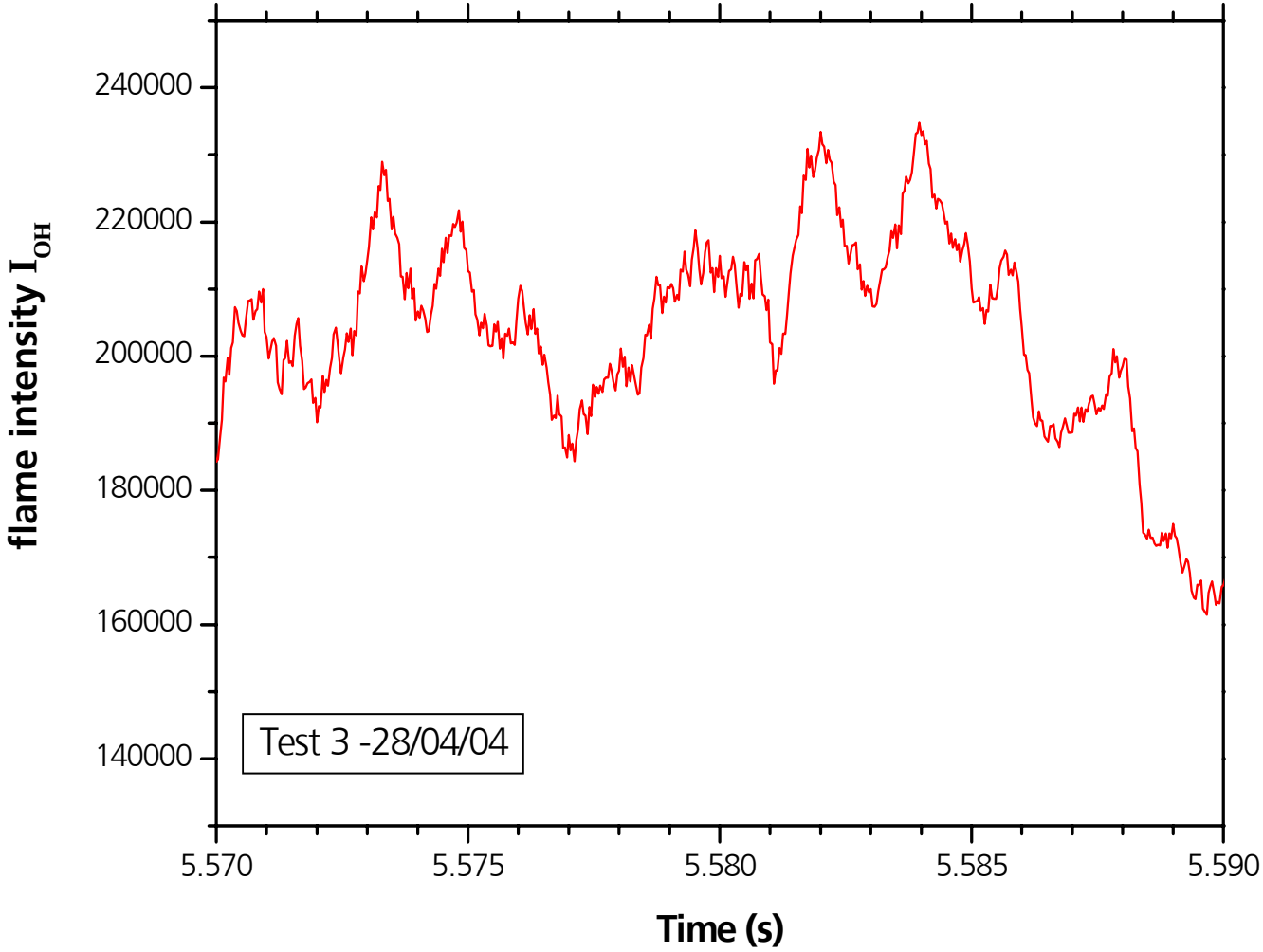


excitation with SN at 180°





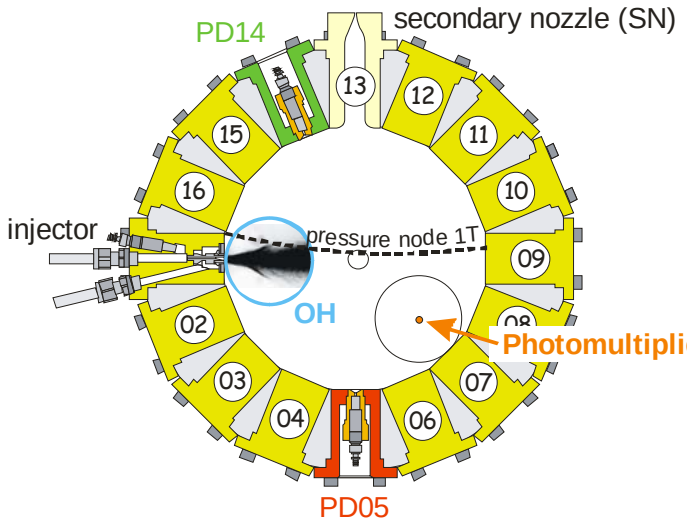
OH-chemiluminescence during excitation

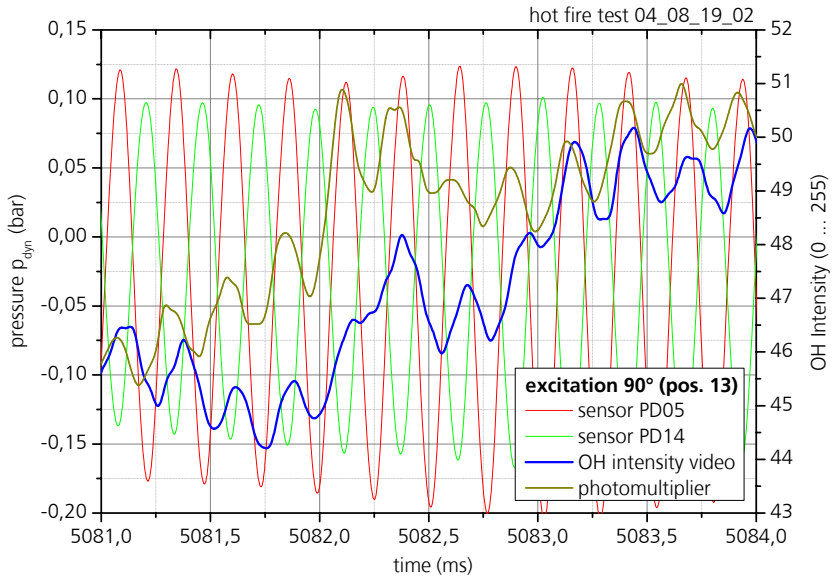


intensified CCD, 27KHz, filter with transmission at 300-310nm

combustion response

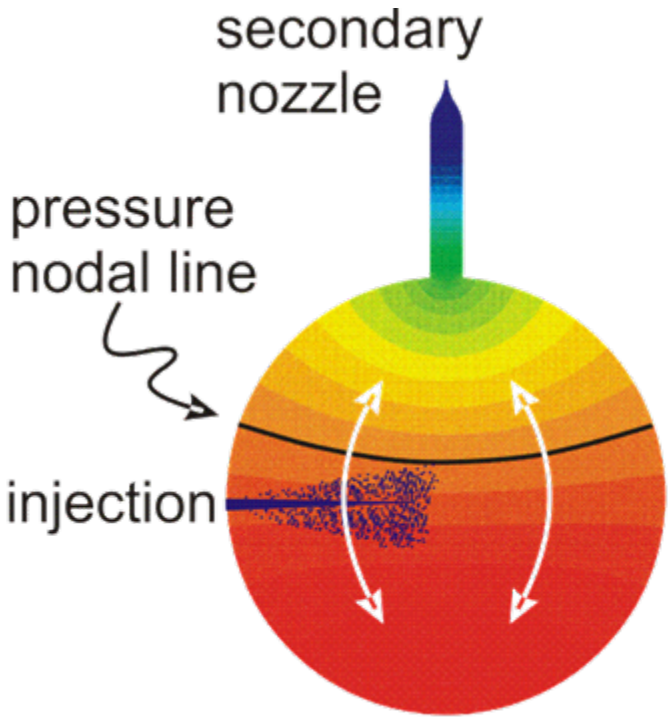
- fluctuation of pressure and OH-emission in phase:
  - positive coupling of combustion and acoustics (Rayleigh criterium)
- excitation levels up to p'/p ~ 20%: no combustion instability observed
  - damping effects suppress gain due to positive coupling
- excitation level did not show any correlation with injection conditions (J, We, R_V, ...)
  - no coupling of acoustics to spray processes in the experiments

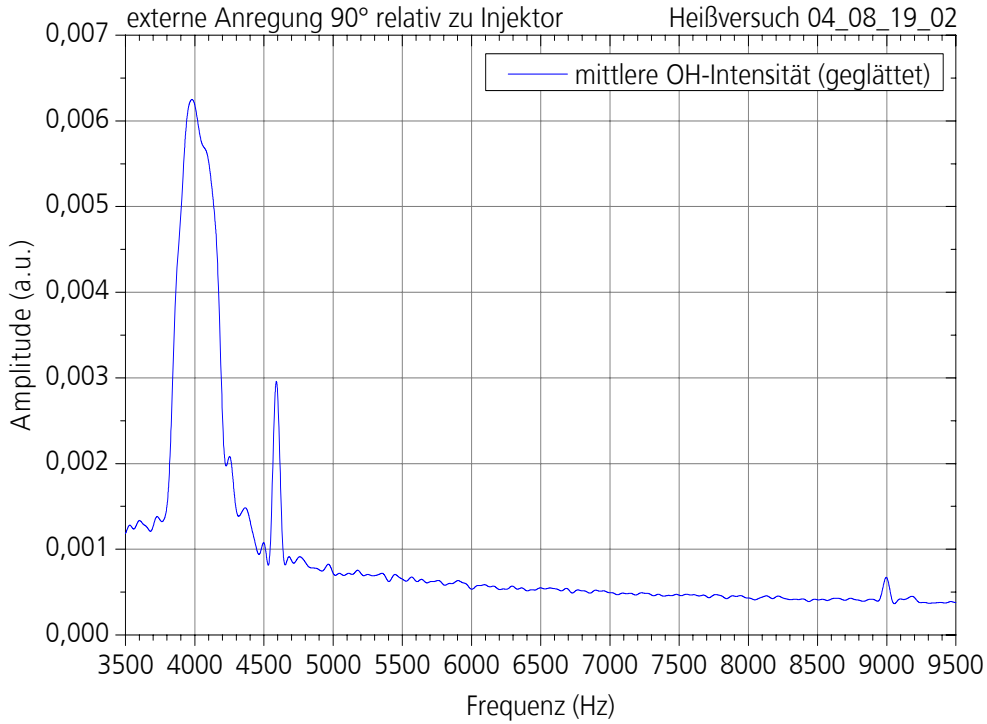




combustion response

- at excitation with SN at 90° no significant frequency component at 2ω
  - coupling due to pressure sensitive processes





interaction index

- Rayleigh Kriterium: $\int_V \int_t Q' \cdot P' \, dt dV$

- response factor:

$$p = \bar{p} + p' \cdot \cos(\omega t)$$

harmonic time dependency

$$\bar{Q} = \bar{\dot{Q}} + \dot{Q}' \cdot \cos(\omega t + \varphi)$$

$$N = \frac{\int_V \int_t (Q'/\bar{Q}) \cdot (p'/\bar{p}) dt dV}{\int_V \int_t (p'/\bar{p})^2 dt dV} = \frac{\dot{Q}'/\bar{\dot{Q}}}{p'/\bar{p}} \cdot \cos(\varphi)$$

$$\boxed{N = \frac{I'/\bar{I}}{p'/\bar{p}}}$$

chemiluminescence = heat release

φ=0

mean flame intensity for SN at 90°

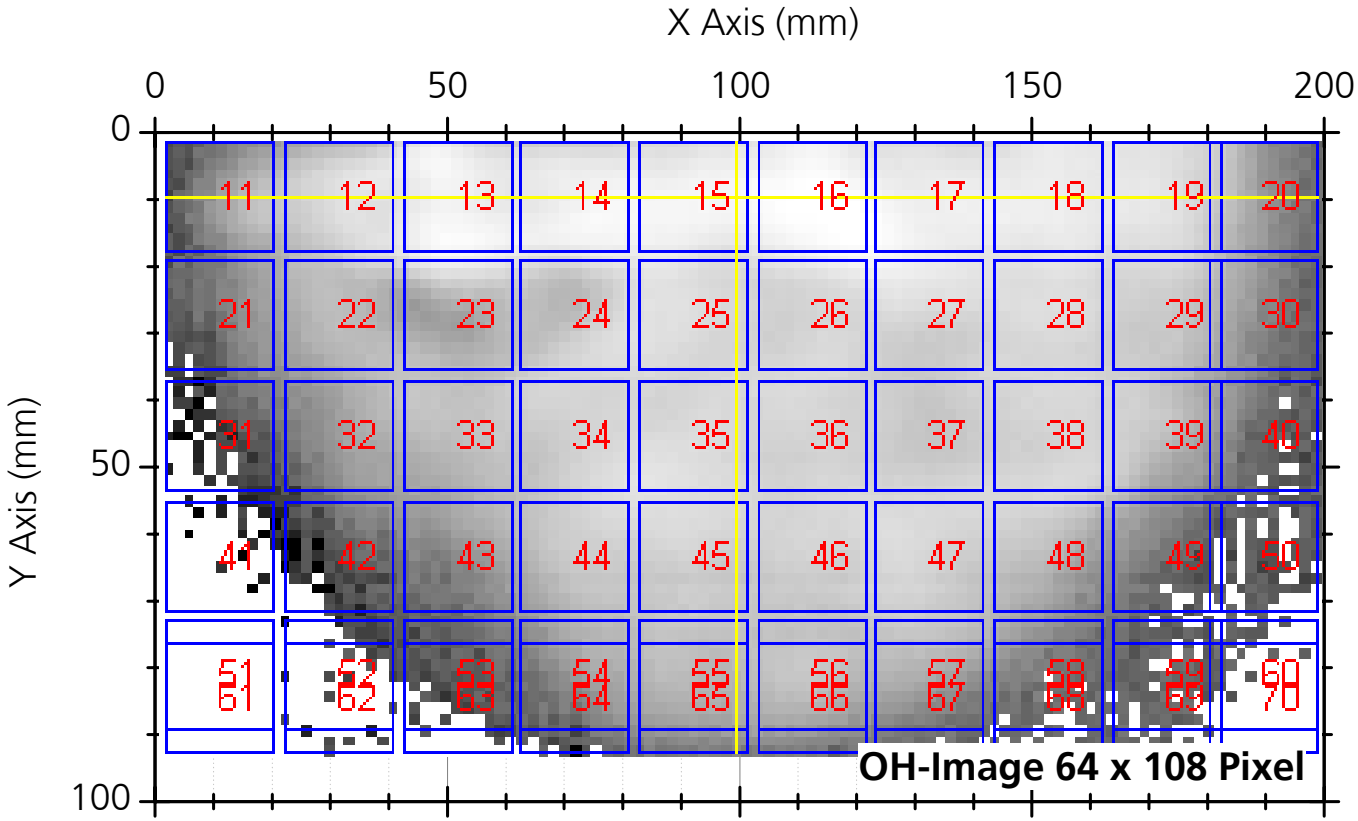
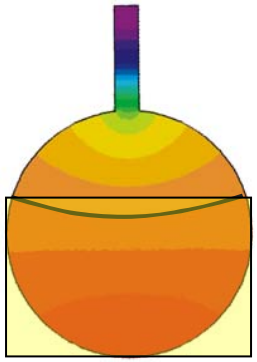
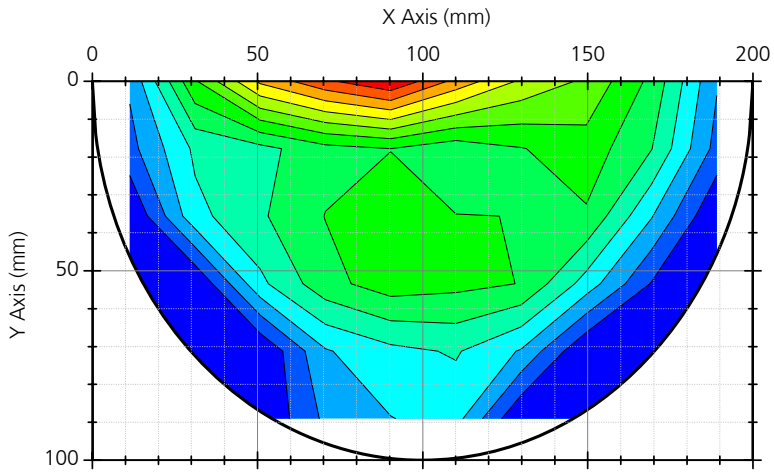


image processing on sub areas

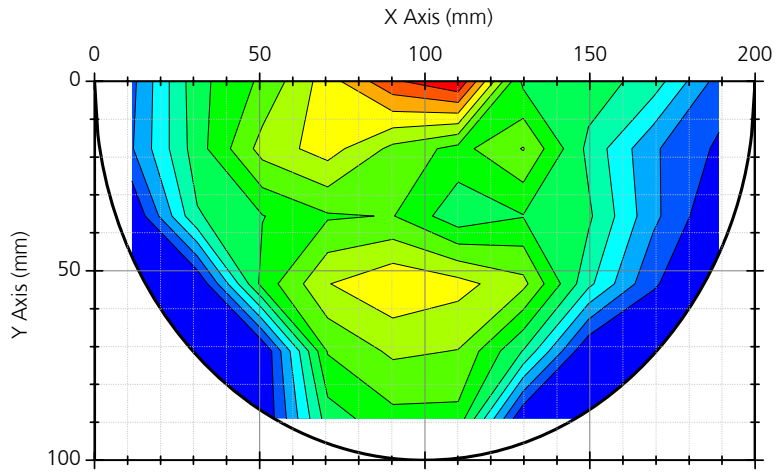
- mean intensity I
- fluctuation I'
- reconstruction of pressure field p, p' from dynamic pressure sensors

interaction index for SN at 90°

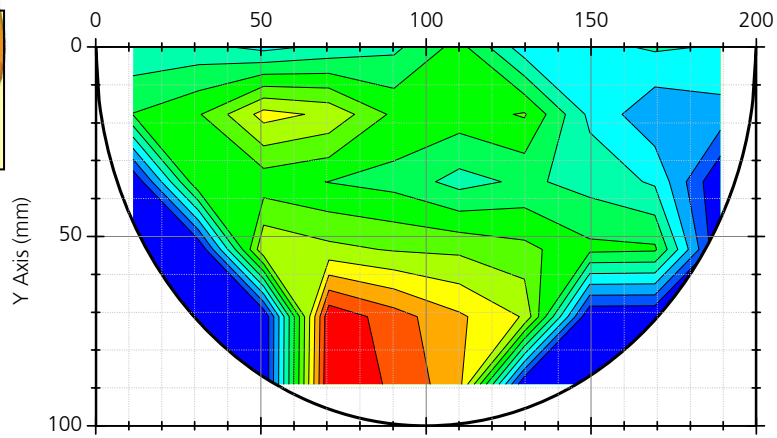




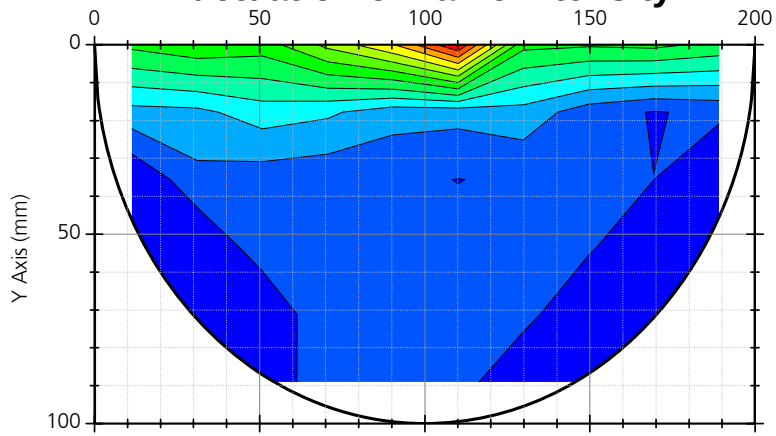
mean flame emission I



fluctuation of flame intensity I'

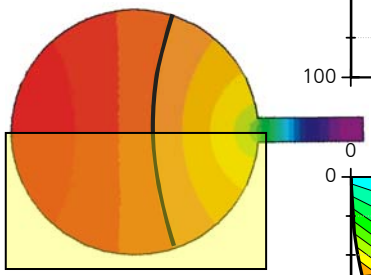


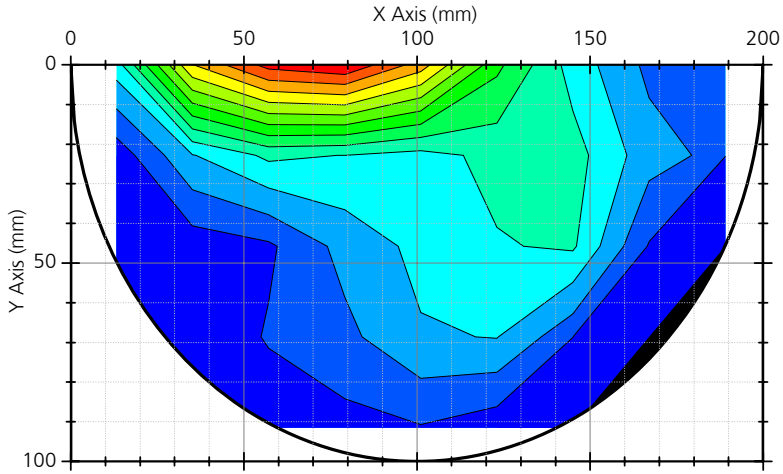
relative flame response I'/I



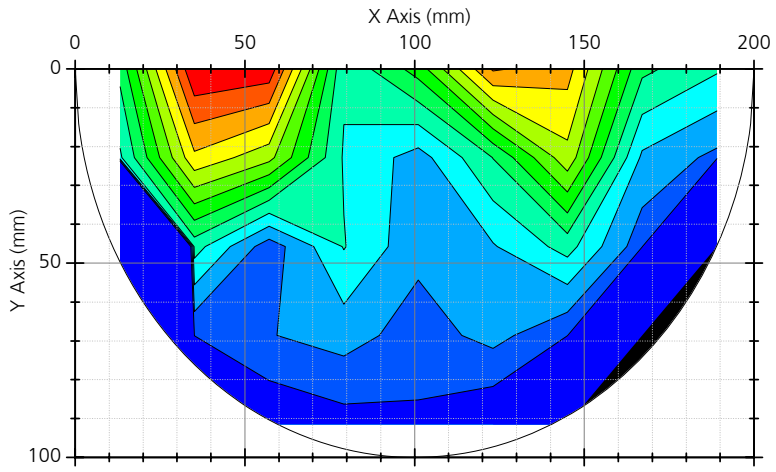
interaction index $(I'/I)/(p'/p)$

interaction index for SN at 180°

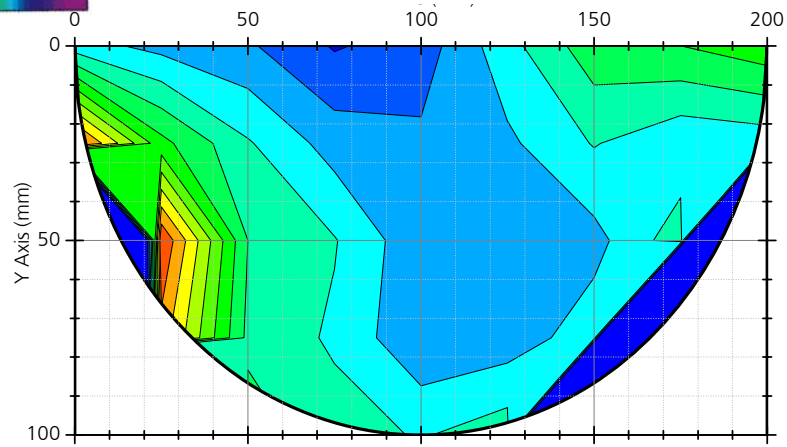




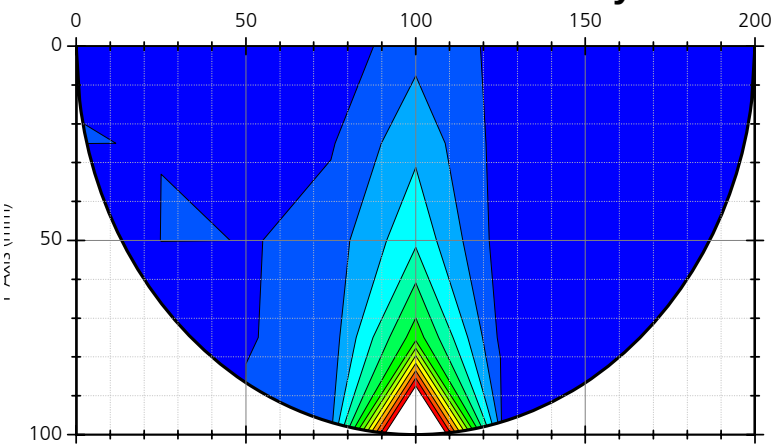
mean flame emission I



fluctuation of flame intensity I'



relative flame response I'/I



interaction index $(I'/I)/(p'/p)$